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Analysis of nonlinear dynamic response for delaminated fiber–metal laminated beam under unsteady temperature field

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ABSTRACT

The nonlinear dynamic response problems of fiber–metal laminated beams with delamination are studied in this paper. Basing on the Timoshenko beam theory, and considering geometric nonlinearity, transverse shear deformation, temperature effect and contact effect, the nonlinear governing equations of motion for fiber–metal laminated beams under unsteady temperature field are established, which are solved by the differential quadrature method, Nermark-β method and iterative method. In numerical examples, the effects of delamination length, delamination depth, temperature field, geometric nonlinearity and transverse shear deformation on the nonlinear dynamic response of the glass reinforced aluminum laminated beam with delamination are discussed in details.

1. Introduction

The Fiber–Metal Laminates (FMLs) [1], a class of composite materials composed of alternately bonded metal layers and fiber composite layers, exhibit the properties of both metals and composites, therefore, FMLs have high strength and stiffness to weigh ratio, excellent fatigue resistance and damage tolerance properties. With all these advantages, FMLs have gained widespread use in aerospace industry during the past decades.

The delamination, which will weaken the mechanical properties and notablely reduce the service life of the structures, initiates easily in the laminated structures, hence it is meaningful and essential to study the FMLs with delamination. In the process of vibration, the contact effect must be considered for analysis of the dynamic problem of FML with delamination damage, otherwise the penetration will occur to the delamination regions, which is impossible in physics. To the best of the authors' knowledge, the nonlinear dynamic response problem for the FML beam with delamination considering the contact effect between delamination interfaces has not been reported so far. However, most of the studies on the dynamic problem for delaminated fiber reinforcement composite laminated materials have not considered the contact effect. Based on the higher-order shear deformation theory, Nagesh and Hanagud [2] analyzed the vibration problem of delaminated composite materials using the finite element method. Wang et al. [3] studied the free vibration of split beams, and concluded that short delamination does not have a visible impact on the natural frequency of the beam which is verified by experiments. Shen and Grady [4] analyzed the effect of delamination on the vibration frequency of the beam by theory and experiments. Kim et al. [5] investigated the dynamic problem of composite laminated plate with multiple delamination using the

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Nomenclature

L, h thickness of the whole fiber–metal laminated beam
$L^{(i)}, h^{(i)}$ $(i=1,2,3,4)$ length and thickness of each sub-beam
$\Omega^{(i)}$ four sub-beams of the fiber–metal laminated beam
θ_k angle at which the k-th layer is laid
$u^{(i)}, w^{(i)}$ displacements of an arbitrary point in region $\Omega^{(i)}$ throughout x, z direction
$\psi^{(i)}$ angle that the section rotates along the neutral axis
$u_0^{(i)}$, $w_0^{(i)}$ displacement components of the points on the mid-plane
$\varepsilon_{xx}^{(i)}, \varepsilon_{xz}^{(i)}$ strains of an arbitrary point in region $\Omega^{(i)}$
$\overline{\varepsilon}_{xx}^{(i)}, \overline{\varepsilon}_{xz}^{(i)}$ strains of the corresponding points on the mid-plane
$\overline{\kappa}_x^{(i)}$ curvature on the mid-plane
$\sigma_{xx}^{(i)k}$, $\tau_{zx}^{(i)k}$ normal stress and shear stress of any point on the k-th layer
Q_{ij}^k, α_x^k stiffness factors and thermal expansion coefficients of the k-th layer
ΔT variation of the temperature
E, μ, ζ, ρ Young's modulus, Poisson's ratio, shear stress modified coefficient and density
$N^{(i)}, Q^{(i)}, M^{(i)}$ membrane stress resultants, shear stress resultants and stress couples
$q^*(x,t)$ contact force
Π total potential energy per unit width
$U^{(i)}$ strain energies of unit volume in the region $\Omega^{(i)}$
$\mathbf{d}^{(i)}$ displacement vectors in the region $\Omega^{(i)}$
$P_c^{(i)}$ coefficient of contact effect in the region $\Omega^{(i)}$
T_t, T_b temperature on the top and bottom surfaces of beam
ρ^k, c_p^k, γ^k mass density, specific heat and thermal conductivity of the k-th layer

improved layerwise theory. Luo and Hanagud [6] proposed a new model to study the dynamic problem of delaminated beam, and demonstrated the efficiency of the proposed model by experiments.

The temperature of working conditions greatly changes when FMLs are used in the field of aerospace industry, therefore it is greatly meaningful in practical engineering to investigate the dynamic response of the FML beam considering the action of unsteady temperature field. Only a few literatures have been reported concerning the thermal problem of composite laminated structures and FML structures. Shen et al. [7,8] investigated the thermal buckling and post-buckling of fiber reinforced composite laminated plate under steady temperature field. Botelho et al. [9] studied the tensile and compressive properties of FML thin plate under hygrothermal conditions, and pointed that hygrothermal conditions cannot evidently weaken the stiffness of the FML plate compared with glass fiber reinforcement laminated plates. Xue et al. [10] used a new method, thermal expansion clamp, to reduce thermal residual stress in carbon fiber aluminum laminates (CALL) without reduction in the tensile stiffness of CALL, and demonstrated the efficiency of the method by experiments. Park et al. [11] indicated that the influence of bond strength between delamination interfaces on the mechanical properties of FMLs is significant under long-term hygrothermal conditions. Therefore, at present, the research activities about FML structures under thermal condition, let alone the dynamic response of FML structures under unsteady temperature field, have not been deepen.

To sum up, the research on nonlinear dynamic response of delaminated FML structures considering unsteady temperature field and contact effect between delamination regions have significant worth in theoretical analysis and applicable value in engineering. In this paper, considering geometric nonlinearity, transverse shear deformation, temperature effect and contact effect, the nonlinear governing equations of motion for FML beams under unsteady temperature field are established. Moreover, all derivative items relative to the space coordinate variable are scattered by the differential quadrature method, derivative items relative to the time are scattered by the Newmark-β method, and the nonlinear items in the governing equation are linearized, and then the whole problem is solved by the iterative method. In numerical examples, the effects of delamination length, delamination depth, temperature field, and transverse shear deformation on the nonlinear dynamic response of the FML beam with delamination are discussed in details.

2. Fundamental equations

Consider a FML beam with a throughout width delamination located in the global coordinate system oxz as shown in Fig. 1. The beam has length L and thickness h. Assume that the FML beam composed by alternately bonded metal layers and fiber composite layers has M layers. When k is an odd number, the layer k is a metal layer, otherwise, the layer k is a fiber layer. The k-th $(k=1,\cdots,M-1)$ interface is located between layer k and layer $k+1$. Let $z_k (k=1,\cdots,M-1)$ denote the distance between the k-th interface and the upper surface, clearly, z_0 and z_M are the upper and lower surfaces of the delaminated beam. The whole delaminated beam is divided into four sub-beams denoted by $\Omega^{(i)} (i=1,2,3,4)$, and the sub-beams are numbered as 1, 2, 3 and 4. It is assumed that the length of each sub-beam is, respectively, $L^{(i)}$, and the heights of sub-beam 2 and 3 are $h^{(2)}$ and $h^{(3)}$, obviously $L^{(2)}=L^{(3)}$, $L=L^{(1)}+L^{(2)}+L^{(4)}$, and $h=h^{(2)}+h^{(3)}$. The local coordinate system $o^i x^i z^i$ is established at the mid-surface of the i-th sub-beam. The domain of each sub-beam along axis $x^{(i)}$ is $[0, L^{(i)}]$, and the domains of sub-beams along axis $z^{(i)}$ are $[0,h]$, $[0,h^{(2)}]$, $[h^{(2)}, h]$ and $[0,h]$, respectively.